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OPTICAL JOHNSON NOISE THERMOMETRY[1]

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For Presentation to the NASA Technical Workshop on Non-Contact Temperature Measurement, Pasadena, California, January 17-19, 1989

Abstract

A concept is being explored that an optical analog of the electrical Johnson noise may be used to measure temperature independently of emissivity. The concept is that a laser beam may be modulated on reflection from a hot surface by interaction of the laser photons with the thermally agitated conduction electrons or the lattice phonons, thereby adding noise to the reflected laser beam. If the "reflectance noise" can be detected and quantified in a background of other noise in the optical and signal processing systems, the reflectance noise may provide a noncontact measurement of the absolute surface temperature and may be independent of the surface's emissivity.

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1 Work Performed for The National Aeronautics and Space Administration, The Marshall Space Flight Center under Interagency Agreement DOE No. 1281-B019-A1

2 Operated by Martin Marietta Energy Systems, Inc. for the U. S. Department of Energy under Contract No. DE-AC05-840R21400

Introduction

Uncertainties in the emissivity of metal specimens cause uncertainties in the measurement of their temperature using conventional radiometric techniques. These uncertainties may be minimized by using multiple wavelength radiometry or by ancillary measurements of surface reflectivity which is related to surface emissivity. A method for absolute radiometric measurement of surface temperature that is independent of emissivity or material properties has not been developed heretofore. Such a method may result from studies of an optical analog of the electrical Johnson noise thermometer.

Conventional radiation thermometry -- and indeed, most instruments -- use intensities or dc levels for measuring the temperature of materials, and are necessarily dependent on knowledge of some physical property of the material: resistivity, emissivity, Seebeck coefficient, acoustic modulus, etc. Superimposed on these dc levels is noise that limits the precision with which the temperature can be determined. Good thermometric practice would reduce the noise to a minimum. This noise, however, contains some information that can be used to indicate some conditions of the specimen, the measuring system, or the specimen's environment.

Johnson and Nyquist[(1)] in 1928 attempted to eliminate noise from radio receivers and found that an irreducible minimum noise was produced by passive components in electrical circuits with no current flow. The magnitude of this noise depends on the absolute temperature of the component, but not on its material composition. The relationship between measured noise, the absolute temperature (T), and the ohmic resistance (R) of the component is given (for $h\nu/kT \ll 1$) by:

$$\overline{V_n^2} = 4\,k\,T\,R\,\Delta f \qquad \overline{I_n^2} = 4\,k\,T/R\,\Delta f$$

$$T = \sqrt{P_n^2}/4\,k\,\Delta f \qquad R_n = \overline{V_n^2}/\overline{I_n^2}$$

where, $\overline{V_n^2}$ is the open-circuit noise voltage spectral density, $\overline{I_n^2}$ is the short-circuit noise current spectral density, measured over a frequency band Δf, h is Planck's constant, k is the Boltzmann constant, and $\sqrt{P_n^2}$ is the noise power, defined as the product of the open-circuit voltage and short-circuit current. These relations [(2)] hold at frequencies up to about 100 GHz. For a 100-Ω resistor at a temperature of 300 K and noise measured over a 60-kHz bandwidth, the noise voltage is about 0.32 μV rms, the noise current is about 3.2 nA rms, and the noise power is about 10^{-15} W.

Johnson noise is produced by the thermal agitation of the free electrons in a solid or liquid as a result of electron-phonon interactions with the lattice atoms. The noise power is independent of the resistor material and depends only on the absolute temperature. The relationship between noise power and temperature is linear.

Electrical Johnson noise thermometry has used various measurement schemes(3), including; (a) the ratio of noise voltages produced by two resistors, one at a known temperature, where both resistances can be measured, (b) separate measurement of noise voltage and noise current on a single resistor, from which noise power can be calculated, and (c) several tuned RLC circuits from which temperature can be obtained from a noise voltage and a capacitance measurement. Signal correlation circuits have been employed to greatly reduce the noise contribution of the measuring system. Lacking a direct electrical measurement of noise power, two measurements must be made in each case to obtain temperature independent of sensor resistance. A "noise resistance" can also be obtained from the ratio of the noise voltage and noise current, which is roughly equal to a measured dc resistance.

Electrical Johnson noise thermometry has been used (a) to measure temperatures in high nuclear radiation environment(4), (b) to establish an absolute thermodynamic temperature scale, (c) to perform in situ calibration of platinum resistance thermometers installed in nuclear plants(5), and could be used (d) in high-pressure or high-magnetic field environments(6). It is presently being engineered for long-term, high-radiation, high- -temperature measurements in space nuclear reactors.

Adaptation of Johnson Noise to Noncontact Thermometry

For Johnson noise techniques to be applied to noncontact thermometry, some method of quantifying the noise power of the electrons in a specimen without making any physical contact must be devised. An approach, now being considered, is the detection of the modulation of a laser beam incident on a hot surface by the interaction of the laser photons with the surface's conduction electrons. It is proposed that an increase in the noise content of the reflected laser beam should be proportional to the noise of the electrons, depend on the surface temperature, and be independent of the surface composition and its emissivity.

Two forms of cptical noise modulation may occur. The first is an amplitude modulation due to scattering of the incident laser beam. The second is a laser line-width broadening due to energy transfer between the incident photon and the surface electron. These mechanisms are shown diagrammatically in Figure 1.

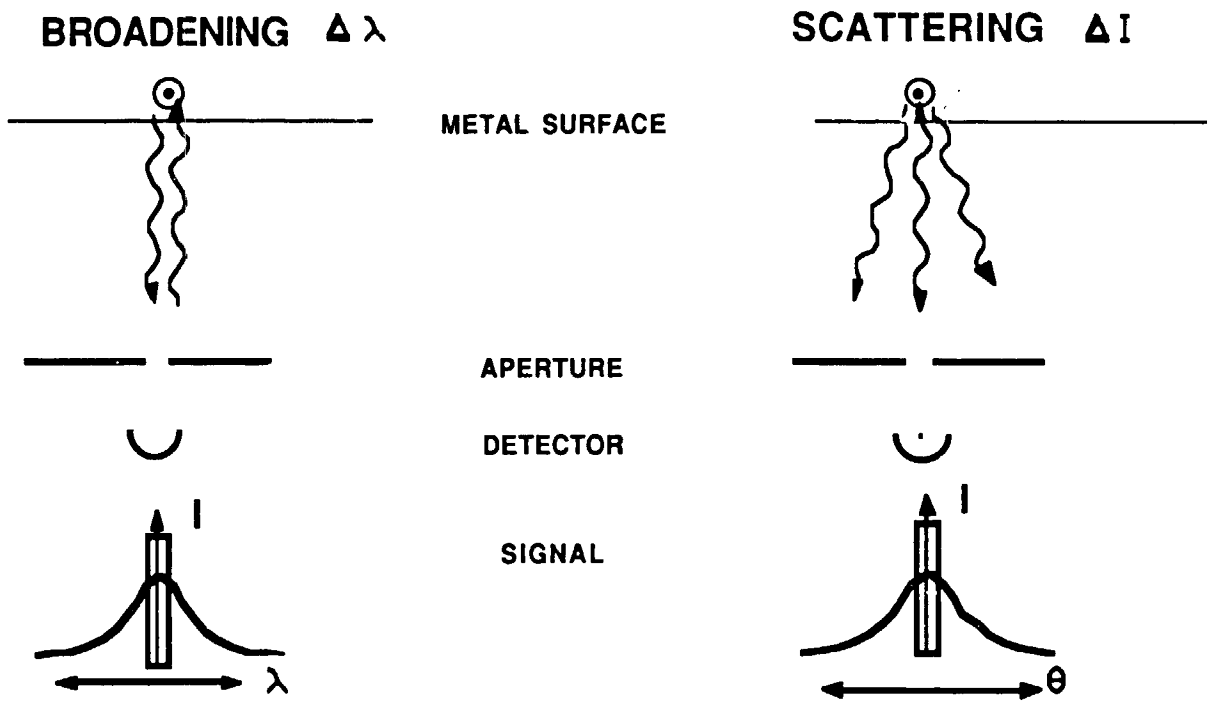

Figure 1. Simplified Mechanisms for Photon-Electron Interaction in Reflectance Noise Thermometry

If the reflectance noise modulation is directly related to the noise power spectral density of the conduction electrons, then only one type of noise measurement would be required to obtain temperature. The electrical Johnson noise measurements require two independent determinations of noise voltage and noise current (or their equivalent) to obtain noise power. The reflectance noise power could be independent of surface emissivity. If not, a second independent optical measurement such as line-broadening may be required to provide two independent measurements of surface temperature that could be combined to give a temperature independent of emissivity.

Implementation of Optical Noise Signal Processing

Various continuous (CW) lasers are available in the laboratory for evaluating these phenomena and several relevant characteristics are shown in the table.

Table 1. Lasers Evaluated for Reflectance Noise Thermometry

Laser Type	Laser Power	Laser Wavelength	Laser Noise
He-Cd	8 mW	325 nm	5%
He-Ne	3 mW	632.8 nm	0.09%
Ar Ion MultiLine	300 mW 100 mW	457-514 nm @ 488 nm	0.5%

Important considerations in selecting the laser are (1) a short wavelength and large power are desirable to minimize the relative contribution of the Planck radiation at the laser's wavelength, (2) low inherent laser noise is desirable, and (3) possible variations in the thermal noise modulation level as a function of the laser wavelength.

The illumination of the photodetectors by a hot surface and a laser beam reflected from the hot surface contains both dc (intensity) and ac (noise) components. These components and an estimate of their magnitudes are shown in Figure 2 for the He-Ne laser.

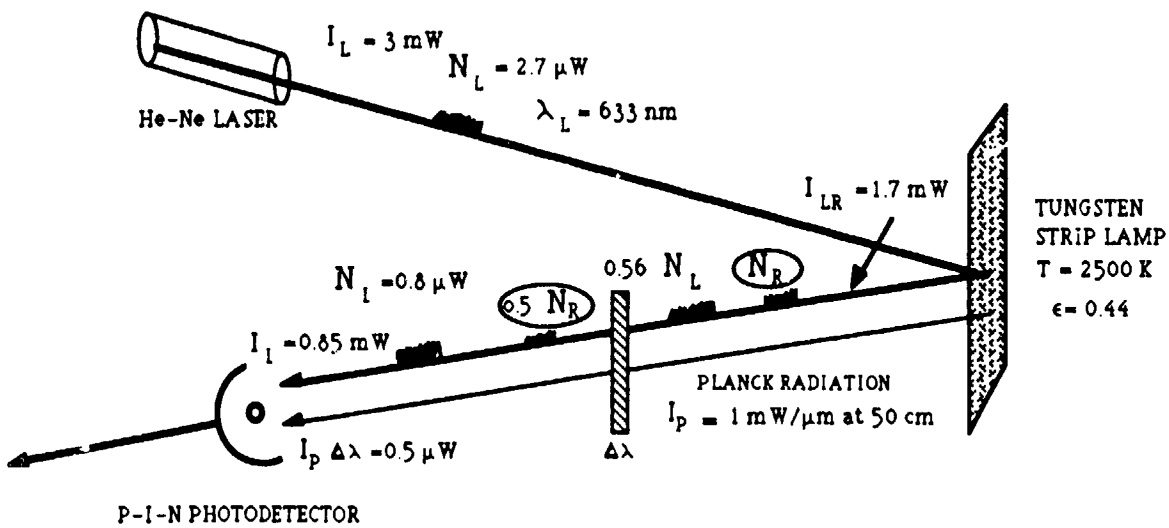

Figure 2. Laser Illumination of a Hot Surface

The dc components of the photodetector signal can be electrically separated from the ac components by filtering and signal subtraction. The dc illumination includes the reflected laser beam intensity and the Planck radiation from the hot surface. Signal channel ac gains may be balanced using high-level, low-frequency modulation of the incident laser beam. The dc levels are not used to provide information about the surface temperature. A system for signal correlation is shown in Figure 3.

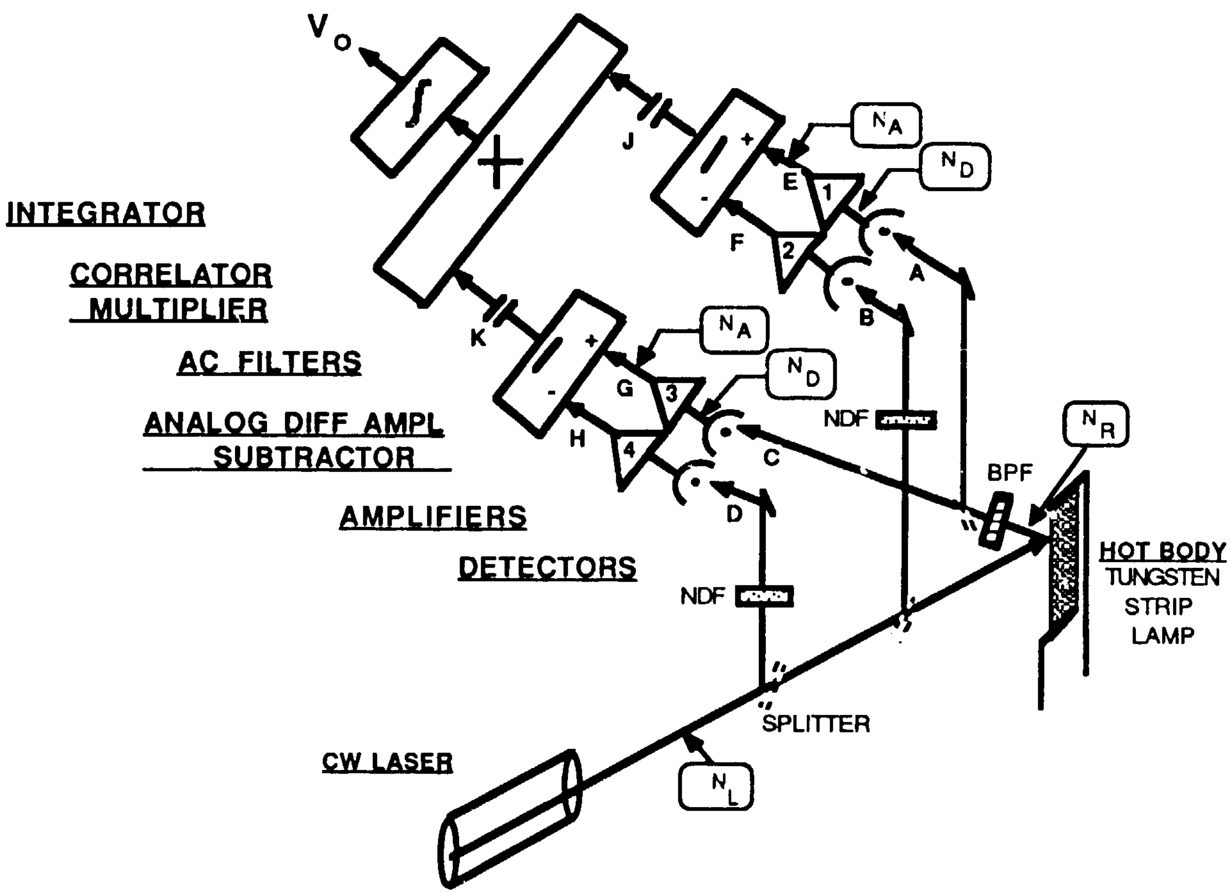

Figure 3. Signal Correlation System for Reflectance Noise Measurement

The ac components of the photodetector signal must be separated to select only the noise contributed by surface reflection of the laser beam (and possibly, the noise in the Planck radiation from the surface). Other sources of noise in the reflected beam include optical noise generated in the laser and microphonics in the optical system. Additional noise will be added in the measurement channels by shot noise generated in the photodetector and rf noise pickup. Some of the low-frequency noise components can be eliminated by high-pass filtering. The remaining wide-band noise components must be separated by signal processing and correlation, using multichannel optical paths. The largest correlated noise signal component is the laser noise. This noise which is common to all four optical channels, can be reduced by subtraction with analog differential amplifiers. The largest source of uncorrelated noise is the shot noise of the photodetectors. The effect of these uncorrelated noise signals is reduced by the multiplier-integrator stage of the signal processor. If the differential amplifiers and the correlator completely eliminate the laser noise and the uncorrelated nonthermal noise sources, the output of the multiplier-integrator should be proportional to the remaining noise from the reflectance modulation of the laser beam by the hot surface.

Correlation System Performance and Requirements

A preliminary estimate was made of the sensitivity of our present signal processing system to detect thermal noise modulation of the laser beam. This estimate shows a minimum detectable signal of 3 nW of noise power can be detected with an uncertainty of 1%, or $1{:}10^3$ of the laser noise, using the helium-neon laser. The estimate assumes (a) total elimination of the uncorrelated system noise, (b) a common mode rejection ratio (CMRR) of 100 dB in the differential amplifiers, and (c) a laser noise power of 0.1%. To detect a thermal noise power of 10^{-14} W, calculated for T=2500 K and Δf = 60 kHz, with 1% uncertainty requires five orders of magnitude improvement in the signal processor sensitivity. This improvement may be accomplished by decreasing the laser noise contribution, increasing the CMRR of the differential amplifiers, and modifying the bandwidth of the signal processor. Adequate rejection of the shot noise in the detectors, which is the major noise contribution of the measuring system, may require unreasonably long integration times for the correlation process to reduce this noise to a level below that of the reflectance noise.

The above analysis assumes that a laser beam can be modulated by another noise source, such as the proposed hot-surface reflectance, over any bandwidth of interest. The unexplored question is whether the electron-photon power transfer process in surface-reflectance signal modulation is efficient at frequencies below 1 MHz.

No estimates have yet been made for possible noise associated with the Planck radiation from the hot surface, nor have we assessed the possibility of measuring the line broadening (see Figure 1) to determine temperature.

Further work on this program will (a) continue the development of a signal processor with improved common mode rejection and larger bandwidth, (b) theoretical investigation of the electron-photon modulation process at a hot surface, (c) reduction of the laser noise and extraneous noise sources in the system, and (d) investigation of line broadening in hot-surface reflection.

Conclusions

A postulated phenomenon of temperature-dependent reflectance modulation of a laser beam is being investigated to determine whether it might provide a means of noncontact surface temperature measurement that is independent of the emissivity of the surface. Methods of signal processing are being developed for eliminating the nonthermal noise sources from the desired thermal reflectance noise. A preliminary estimate indicates that the signal correlation system may need to extract one part of desired noise from a background at least eight orders of magnitude larger.

References

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OPTICAL JOHNSON NOISE THERMOMETRY

A STUDY PERFORMED FOR THE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
THE MARSHALL SPACE FLIGHT CENTER

UNDER INTERAGENCY AGREEMENT DOE NO. 1281-B019-A1

BY

OAK RIDGE NATIONAL LABORATORY
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FOR PRESENTATION TO

NASA TECHNICAL WORKSHOP
ON NON-CONTACT TEMPERATURE MEASUREMENT
PASADENA, CALIFORNIA
JANUARY 17-19, 1989

MARTIN MARIETTA

MARTIN MARIETTA ENERGY SYSTEMS, INC.

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OPTICAL JOHNSON NOISE THERMOMETRY

OBJECTIVE

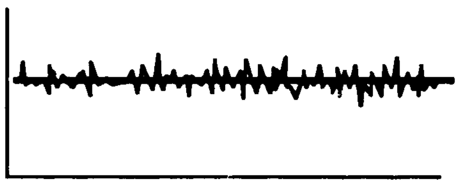
TO INVESTIGATE A NEW CONCEPT OF TEMPERATURE MEASUREMENT BASED ON THE DETECTION OF NOISE ADDED TO A LASER BEAM BY ITS REFLECTION FROM A HOT SURFACE. THIS CONCEPT SHOULD BE INDEPENDENT OF THE EMISSIVITY OF THE MATERIAL.

APPROACH

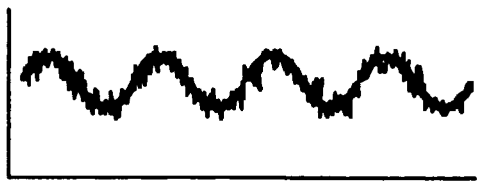
- INVESTIGATE AN OPTICAL ANALOG OF ELECTRICAL JOHNSON NOISE THERMOMETRY.
- ATTEMPT TO DETECT AND QUANTIFY THE NOISE CONTAINED IN A LASER BEAM REFLECTED FROM A HOT SURFACE, WHICH IS MODULATED BY THE THERMALLY-INDUCED AGITATION OF CONDUCTION ELECTRONS IN THE MATERIAL.
- ELIMINATE NON-THERMAL NOISE FROM THE OUTPUT BY CORRELATION TECHNIQUES.
- DEMONSTRATE THE TEMPERATURE DEPENDENCE AND EMISSIVITY INDEPENDENCE OF THE REFLECTANCE NOISE.

NOISE

- **NOISE IS PRESENT IN ALL ELECTRICAL, OPTICAL, AND ACOUSTIC SIGNALS**
- **NOISE LIMITS THE ABILITY OF SIGNALS TO TRANSMIT INTELLIGENCE**



DC SIGNALS



AC SIGNALS

- ***NOISE CONTAINS INFORMATION***

◦ NOISE CAN BE ISOLATED BY FILTERING OR BY SIGNAL CORRELATION TECHNIQUES

NOISE CAN BE USED TO MEASURE TEMPERATURE

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ELECTRICAL JOHNSON NOISE THERMOMETRY

BACKGROUND

- IDENTIFIED IN 1928 BY JOHNSON & NYQUIST (BELL LABS) AS THE LIMITING NOISE CONTRIBUTION OF PASSIVE ELEMENTS IN AMPLIFIERS AND RADIO RECEIVERS

- USED BY GARRISON & LAWSON (UNIV OF CHICAGO) IN 1936 AS A THERMOMETER, EMPLOYING A RATIO TECHNIQUE TO MINIMIZE THE MEASURING SYSTEM NOISE CONTRIBUTION.

- EXTENDED AND APPLIED BY ORNL FROM 1974 USING NOISE POWER MEASUREMENTS FOR THERMOMETRY

PHENOMENA

- JOHNSON NOISE GENERATED BY INTERACTION BETWEEN CONDUCTION ELECTRONS AND THERMALLY VIBRATING LATTICE

- QUANTITATIVELY RELATED TO THE RESISTANCE AND ABSOLUTE TEMPERATURE OF A PASSIVE RESISTOR

$$\overline{V_n^2} = 4\,k\,T\,R\,\Delta f \qquad \overline{I_n^2} = 4\,k\,T/R\,\Delta f$$

$$\sqrt{P_n}^2 = 4\,k\,T\,\Delta f \qquad R_n = V_n/I_n$$

- JOHNSON NOISE IS WHITE OVER ALL FREQUENCIES $< \sim 100$ GHz

- POWER IS $\approx 10^{-15}$ W FOR A RESISTOR AT 300 K

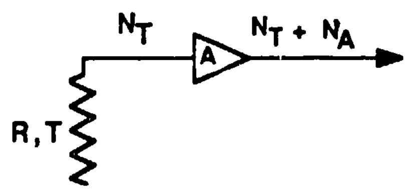
- JOHNSON NOISE IS INDEPENDENT OF MATERIALS PROPERTIES

ELECTRICAL JOHNSON NOISE THERMOMETRY

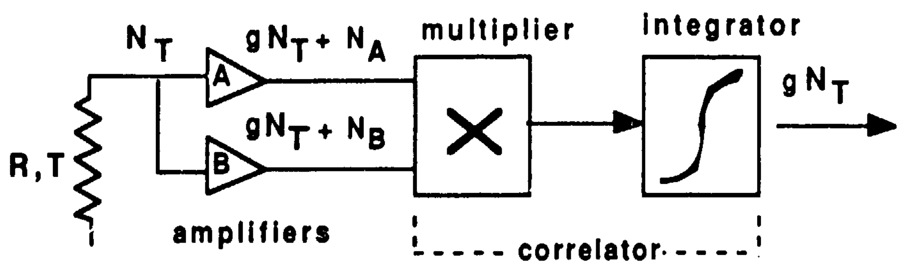
APPLICATION

- TWO INDEPENDENT MEASUREMENTS ARE REQUIRED TO OBTAIN THE ABSOLUTE TEMPERATURE UNIQUELY
- THE NOISE VOLTAGE (CURRENT OR POWER) CAN BE OBTAINED OVER ANY PASSBAND (Δf) OR SUMMED OVER ANY COMBINATION OF PASS BANDS
- THE NOISE CONTRIBUTED BY THE MEASURING SYSTEM CAN BE ELIMINATED BY:

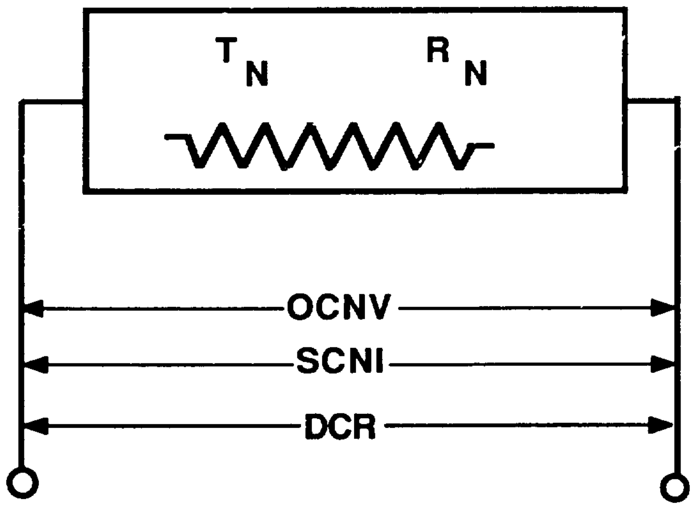
a) MEASUREMENT AND SUBTRACTION OF THE MEASURING SYSTEM NOISE FROM THE OUTPUT NOISE SIGNAL



b) CORRELATION OF NOISE CONTRIBUTED BY TWO VOLTAGE AMPLIFIERS IN PARALLEL



ELECTRICAL NOISE POWER IN A PASSIVE RESISTOR



$$OCV = \sqrt{\overline{E_N^2}} = (4\ k\ \Delta f\ T\ R)^{1/2}$$

$$SCI = \sqrt{\overline{I_N^2}} = (4\ K\ \Delta f\ T/R)^{1/2}$$

$$P_N = V_N\ I_N$$

$$P_N = I_N^2\ R$$

$$P_N = V_N^2\ /R$$

$$T_N = P_N\ / 4\ k\ \Delta f$$

$$R_N = V_N\ / I_N$$

AT $T=300$ K, $R = 100\Omega$, and $\Delta f = 60$ kHz, $V_N = 0.1$ uV, $I_N = 10$ nA, and $P_N = 10^{-15}$ W

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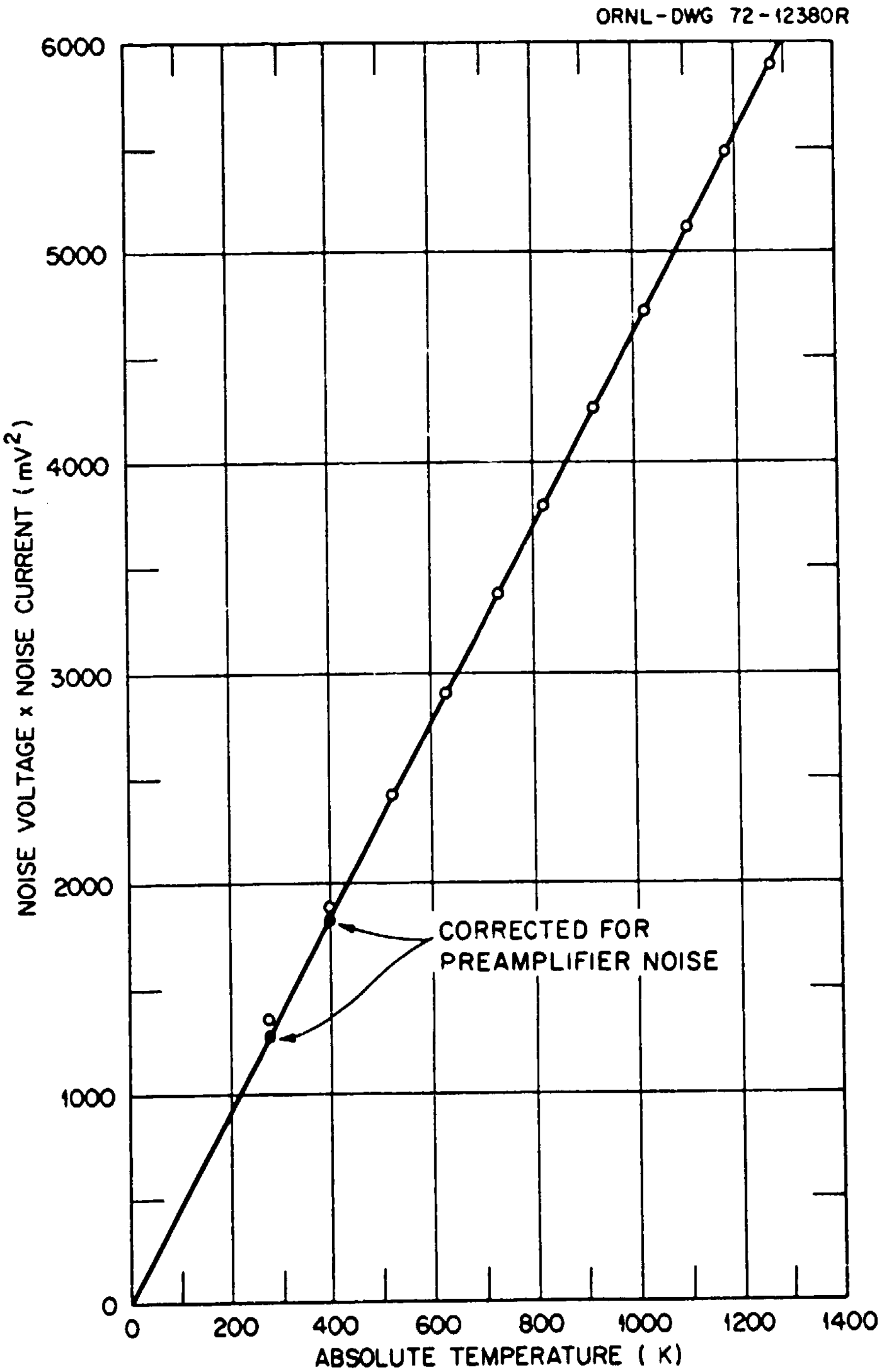
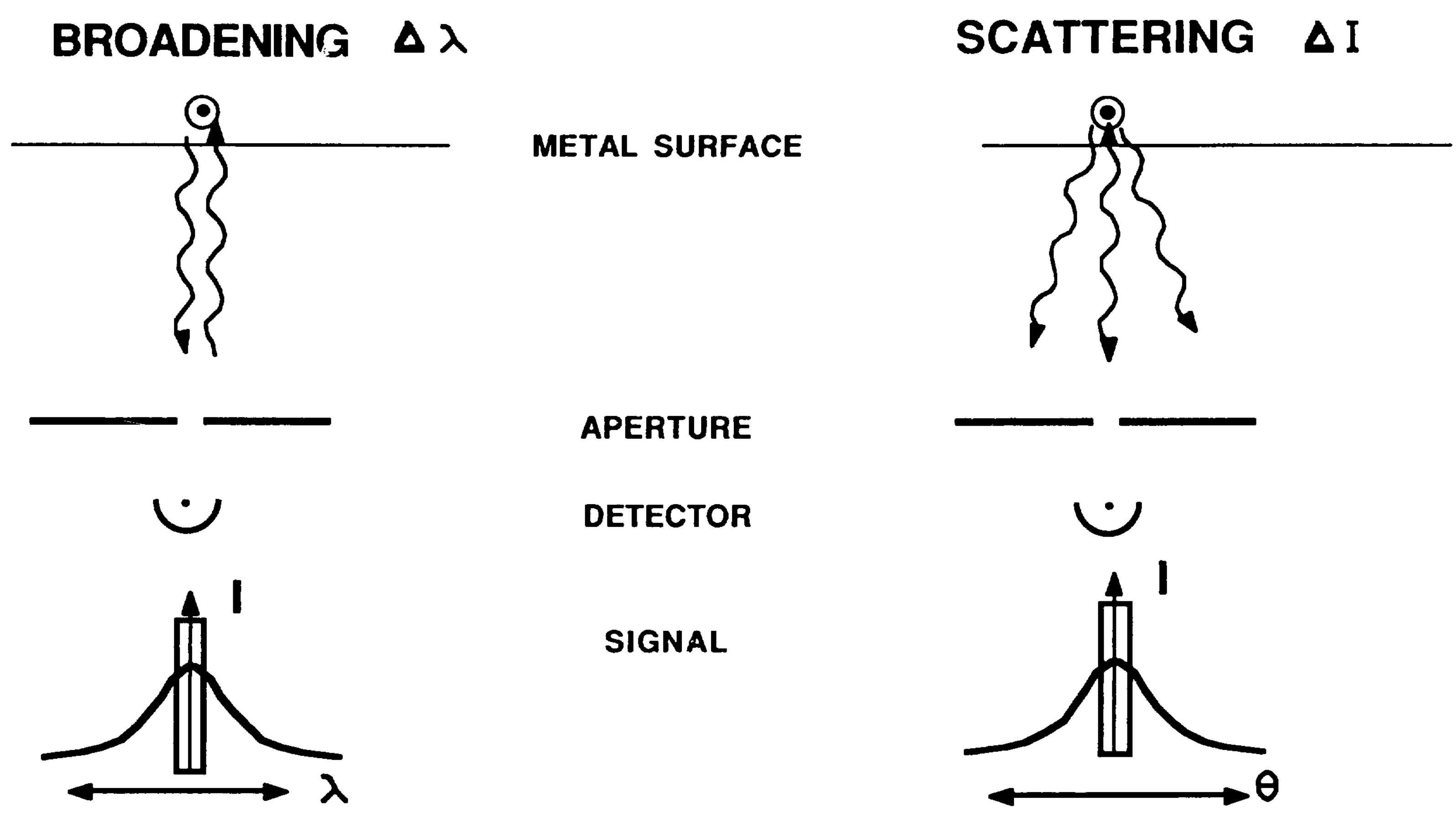
THE JOHNSON NOISE POWER THERMOMETER IS A LINEAR THERMOMETER



THE JOHNSON NOISE POWER THERMOMETER IS INDEPENDENT OF MATERIALS PROPERTIES

SIMPLIFIED MECHANISMS FOR PHOTON-ELECTRON INTERACTION IN REFLECTANCE NOISE THERMOMETERY



TWO ASSOCIATED PHOTON-ELECTRON INTERACTION MECHANISMS
MAY PROVIDE TWO INDEPENDENT OBSERVABLE EFFECTS
THAT CAN BE USED TO ELIMINATE THE EMISSIVITY MATERIAL PROPERTY

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OPTICAL NOISE SIGNAL PROCESSING

1 THE LASER BEAM INCIDENT ON A HOT SURFACE CONTAINS
   - A DC (INTENSITY) COMPONENT AND
   - AN AC (LASER NOISE) COMPONENT

2. THE BEAM REFLECTED FROM THE HOT SURFACE CONTAINS
   - A REDUCED DC LEVEL FROM SURFACE REFLECTION,
   - AN ATTENUATED AC COMPONENT OF LASER NOISE,
   - ADDITIONAL AC NOISE DUE TO LAMP BEHAVIOR, AND
   - AN ADDED AC SIGNAL DUE TO "REFLECTANCE NOISE"

3. THE SIGNAL CHANNELS HAVE AC AND DC GAINS, AND INTRODUCE ADDITIONAL AC NOISE

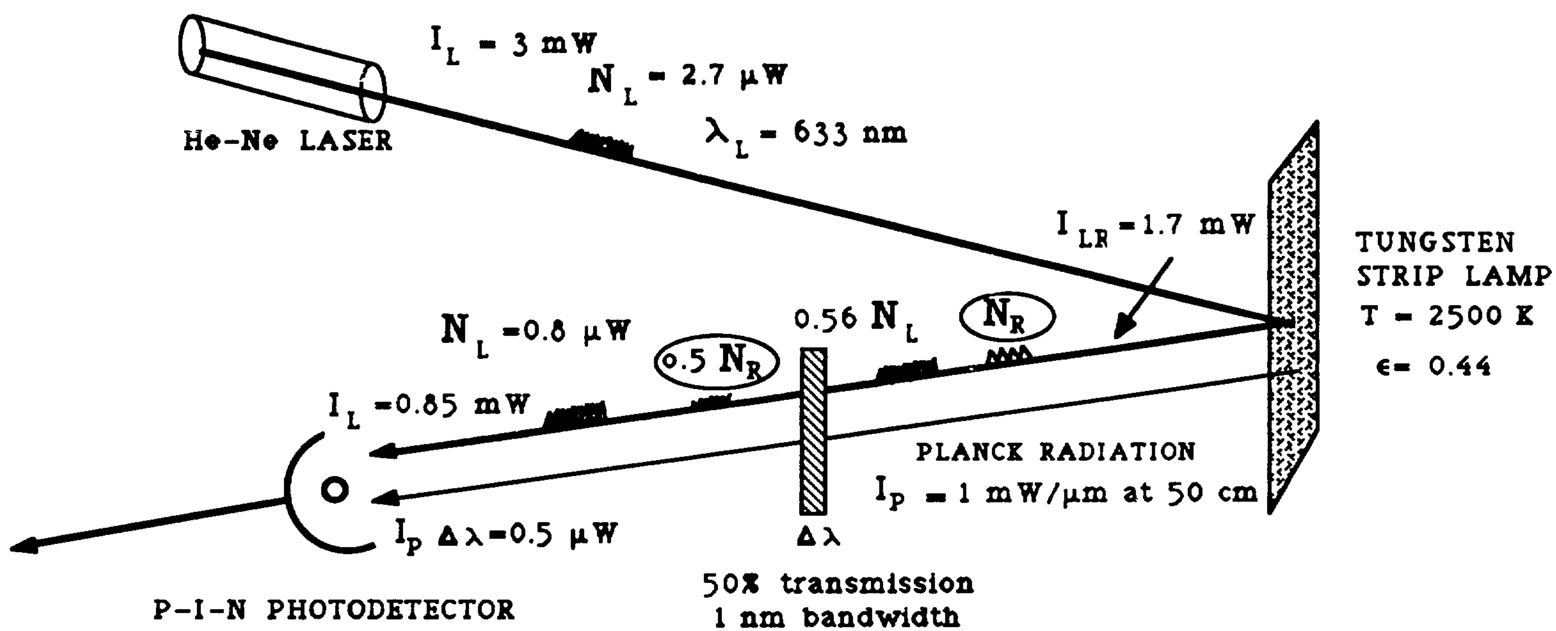
4. BY SUBTRACTION AND CORRELATION, THE DC SIGNAL COMPONENT, THE LASER NOISE, AND THE UNCORRELATED AC NOISE CAN BE REMOVED, LEAVING ONLY CORRELATED AC (NOISE) AT THE OUTPUT

5. THE AC LEVEL CAN BE NORMALIZED BY USING RATIOS OF DC LEVELS

6. THE UNCERTAINTY OF THE FINAL OUTPUT VALUE OF THE REFLECTANCE NOISE DEPENDS ON THE SQUARE OF THE INTEGRATION TIME, THE BANDWIDTH OF THE DETECTION SYSTEM, AND THE STABILITY OF THE TEMPERATURE SOURCE AND THE MEASUREMENT CHANNEL

LASER ILLUMINATION OF A HOT BODY

LASER TYPE	LASER POWER	LASER WAVELENGTH	LASER NOISE
He-Cd	8 mW	325 nm	5%
He-Ne	3 mW	632.8 nm	0.09%
Ar-Ion MultiLine	300 mW 100 mW	457-514 nm 488 nm	0.5%



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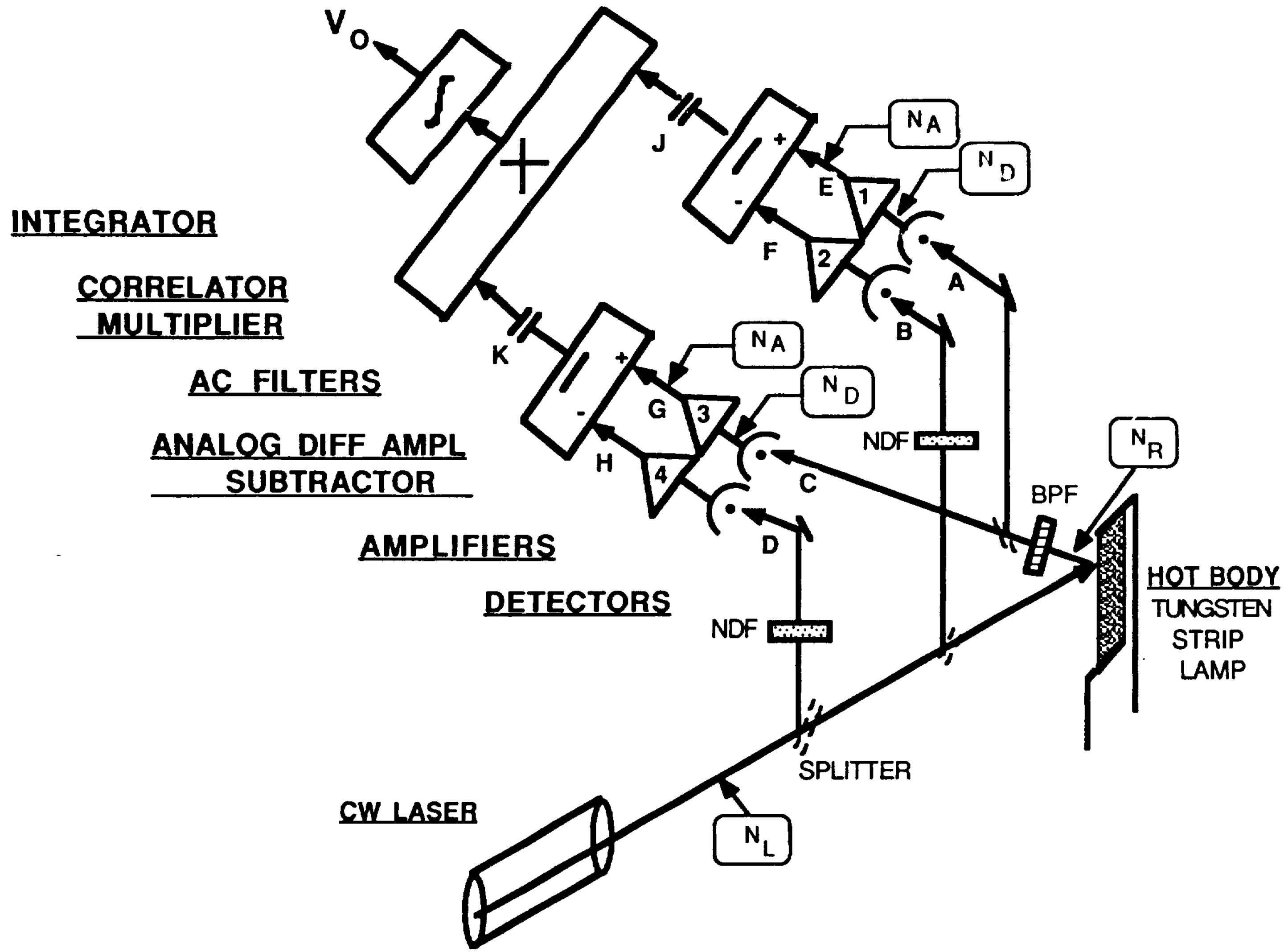
DETECTION OF OPTICAL JOHNSON NOISE IN A LASER BEAM REFLECTED FROM A HOT BODY USING SIGNAL CORRELATION



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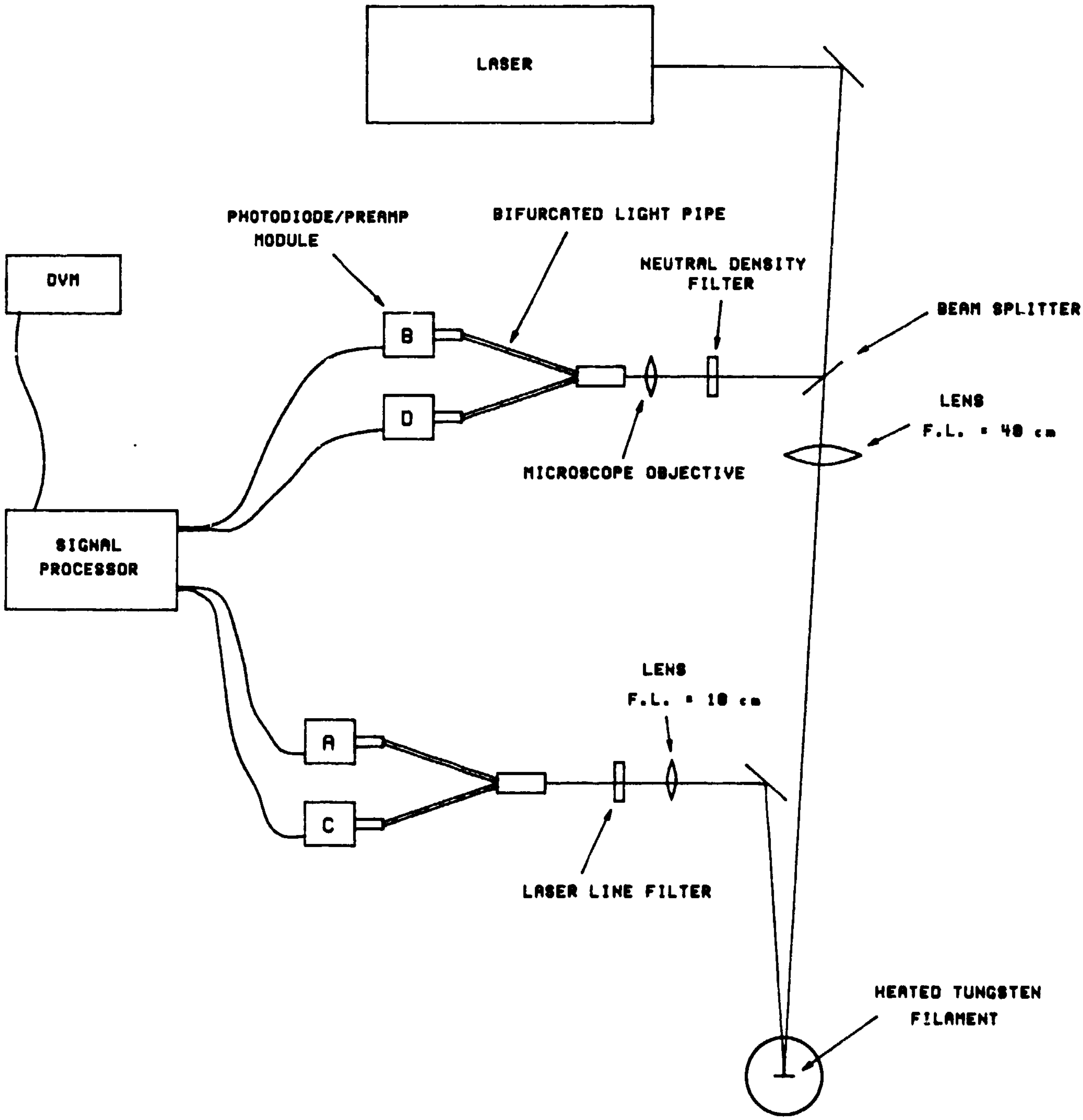

OPTICAL JOHNSON NOISE THERMOMETRY

RESEARCH MEASUREMENT SYSTEM